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EPIPHYTIC LICHEN RECOLONIZATION IN THE CENTRE OF CRACOW (SOUTHERN POLAND) AS A RESULT OF AIR QUALITY IMPROVEMENT

ABSTRACT: Epiphytic lichen distribution and diversity were investigated in seven localities in the centre of Cracow (South Poland). Field studies were carried out in the years 2007–2009. A total of 39 species were recorded at 434 sites; 6 species are new to Cracow. Compared to previous surveys, the overall situation has generally improved, with higher lichen species richness and cover rate. The area of former 'lichen desert' in the city centre has disappeared and it has been colonized by SO_2 sensitive macrolichen species. Dominance of nitrogen- and dust-tolerant species has been observed. The health of lichen thalli has improved and many young specimens were recorded in the study area. These changes follow air quality improvement, mainly the SO_2 decline, during the last twenty years. Transport-related NO_x and dust have become the main pollutants in the centre of Cracow. The recolonization process seems to be not completed yet and further improvement in lichen distribution and diversity is expected. Thus long-term biomonitoring is required.

KEY WORDS: lichens, recolonization, air pollution, SO_2, NO_x

1. INTRODUCTION

Lichens are effective bioindicators of air quality because of their morphological and physiological characteristics (Conti and Cecchetti 2001). They take up water, together with different dissolved contaminants, over the entire surface of the organism, directly from the atmosphere (Nimis and Purvis 2002). Direct relationship between lichen survival and air pollution was first noticed by Nylander in Paris in the year 1866. Numerous further studies have been focused on the influence of sulphur dioxide (SO_2) (*e.g.* Nash 1973) and nitrogen oxides (NO_x) (*e.g.* Nash 1976, van Dobben *et al.* 2001) on lichens. Methods of SO_2 level assessment using epiphytic lichens (*e.g.* Hawksworth and Rose 1970) have been widely used in urban and industrial areas in Europe since 1970s. Lichens have also been used as biomonitors of many other contaminants, *e.g.* heavy metals, fluorides, radionuclides, phosphorus, dioxins, furans (*e.g.* Gilbert 1971, Olech *et al.* 1981, Conti and Cecchetti 2001, Garty *et al.* 2003, Augusto *et al.* 2007, Augusto *et al.* 2009). Lichens respond rapidly to decreasing concentrations of air pollution, thus even annual changes of the air pollutants can be detected using lichens (Loppi *et al.* 2004).

For many years SO_2 has been considered as the main and most harmful substance causing decline of lichens in cities and industrial regions throughout the world (Purvis *et al.*

2003). The places where no epiphytic lichens can exist are called 'lichen deserts' (Purvis *et al*. 2003). The correlation between high concentrations of SO_2 in the atmosphere and lichen decline is well documented (Seaward 1993). Over the last decades emission of SO_2 in most developed countries has started to decrease in response to more severe emission control regulations and socio-economic changes (Bates *et al*. 2001). As a result recolonization of 'lichen deserts' is visible. Recovery of lichen biota and improvement in lichen diversity has been documented in European cities and conurbations such as *e.g.* London (Rose and Hawksworth 1981), Munich (Kandler and Poelt 1984), Paris (Seaward and Letrouit-Galinou 1991), Rome (Munzi *et al*. 2007) and Torino (Isocrono *et al*. 2007) as well as in smaller towns (Loppi *et al*. 2002, Loppi and Corsini 2003, Loppi *et al*. 2003, Hultengren *et al*. 2004, Loppi *et al*. 2004). In many urban areas SO_2 concentrations are today equal or only slightly higher than in surrounding rural areas, while NO_x and other contaminants concentrations are still on a high level (Hultengren *et al*. 2004). This suggests that lichen growth in urban areas is no longer determined by SO_2, but other factors play a major role (Seaward 1997, Purvis *et al*. 2003).

The history of lichen biota of Cracow is well documented. The first studies on lichens in Cracow were carried out in the middle of the 19th century. Problems related to physiography and lichen bioindication were investigated by Lojka (1868), Jabłoński (1872), Berdau (1876), Rehman (1879) and Boberski (1886) (after Kiszka and Kościelniak 1996). Later studies, from the middle of the 20th century, were mostly focused on epiphytic lichens. Zurzycki (1950) presented the first lichenoindication map of Cracow. In the 1970s research on lichens in the city and its surroundings, was undertaken by Kiszka (1977), who documented the negative influence of air contaminants on lichen distribution. In the 1990s an updated lichenoindication map of Cracow was presented by Kiszka and Kościelniak (1996). Both Zurzycki (1950), and Kiszka and Kościelniak (1996) observed large area of 'lichen desert' in the city centre (Fig. 1). During the latest studies (Kiszka and Kościelniak 1996) some young individuals of epiphytic lichens were found in the inner parts of 'lichen desert', which suggested the beginning of a recolonization process.

Despite numerous studies on lichen recovery, there is still few information concerning conurbations of Central Europe, and this work tries to fill this gap. The aim of the study was to investigate the latest changes in epiphytic lichen vegetation and probable lichen recolonization in the centre of Cracow, and also to assess the state of air pollution in this area using lichens as biomonitors. The current study provides a complement to the data about lichen dynamics in urban areas from this part of Europe.

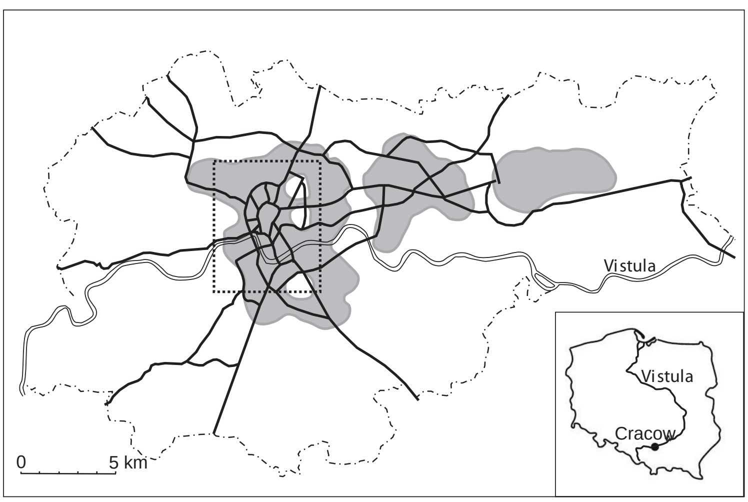

Fig. 1. General overview of Cracow with boundaries of the study area marked with dotted line; grey colour – extent of the 'lichen desert' in 1996 (after Kiszka and Kościelniak 1996).

2.STUDY AREA

Cracow (50°03´41˝N, 19°56´18˝E), the capital of the Małopolska Voivodship, is the largest city in the South of Poland with a population of 755 000 in the area of 327 km^2 (Statistical Office in Cracow 2010). The city is situated in the valley of the Vistula River, between the Jura Highland in the north and the Carpathians in the south (Fig. 1). The main industrial facilities of Cracow are located in its eastern and southern parts, however nowadays there is a tendency to move companies to the suburbs. Currently there are two major sources of substantial air pollution in the city: ArcelorMittal Poland S.A. unit in Cracow (former T. Sendzimir Steelworks) and Heat and Power Station "KRAKOW" SA (Report… 2009). According to the prevailing winds in Cracow, pollutants coming from the adjacent Upper Silesian Industrial Region (in the west) and from a coal-fired electric power station in Skawina (in the south-west from Cracow) have also considerable influence.

2.1 Weather

According to long-lasting monitoring (Matuszko 2007) average annual rainfall in Cracow is 679 mm, most of which is concentrated in summer period (July). Mean annual temperature is 8.7°C. The hottest month is July (18.9°C) and the coldest is January (–2.1°C). The prevailing winds are W and SW. The city location in the Vistula River Valley provides frequent fogs and temperature inversion limiting natural ventilation in the city (German 2007). There are about 25.1% windless days during the year, mostly in autumn (Mikulska-Szostek 1988). Generally, the urban area of Cracow is warmer than its surroundings, which is called an urban heat island (UHI) (Lewińska 2000).

2.2. Air pollution

Rapid industry development in Cracow after the Second World War caused a very severe atmosphere contamination, especially with particulates, SO_2 and NO_x. The major emission source has been the T. Sendzimir Steelworks (former V. Lenin Steelworks; ArcelorMittal Poland S.A. today). In 1965 approximately 124.5 10^3 tons of dust and 358.9 10^3 tons of SO_2 were emitted to the atmosphere in Cracow, of which 53 and 13%, respectively, was emitted by V. Lenin Steelworks (Hess 1969, Bokwa 2007).

Data from the late 1980s and early 1990s shows very high level of SO_2 and particular matter PM_{10} in the air. Since then a significant improvement in air quality in the whole Małopolska Voivodship has been seen, following decrease of industrial emission (Fig. 2). During the last 15 years significant changes in economy led to modernization of technological process and development of companies running according to new, pro-ecological technologies, which resulted in reduction in the pollutants emissions. The average annual SO_2 emission is now about two times lower than in the 1980s, and the level of PM_{10} emission has decreased almost fifteen times (Fig. 3). Nowadays concentrations of

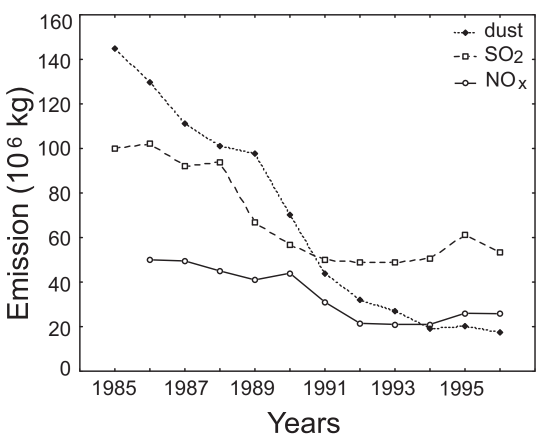

Fig. 2. Changes of dust (PM_{10}), SO_2, NO_x emission levels in the former Cracow Voivodship in the years 1985–1996.

Table 1. List of epiphytic lichen species noted in selected parts of Cracow in the 1970s (Kiszka 1977), 1990s (Kiszka and Kościelniak 1996) and in the years 2007–2009 and their tolerance (T) to nutrients (after Smith *et al*. 2009). Epiphytic species recorded in 2009 only are in bold. *a* – acidophytic, *d* – dust tolerant, *n* – nitrophytic.

Species	T	The Old Town			Urban and industrial region		
		1977	1996	2009	1977[1]	1996[2]	2009[3]
Amandinea punctata (Hoffm.) Coppins & Scheid.	*n*	+	+	+	+	+	+
Bacidina phacodes (Körb.) Vězda		+	+	+	+	+	+
Buellia griseovirens (Turner & Borrer ex Sm.) Almb.		–	–	–	–	+	–
***Candelaria concolor* (Dicks.) Stein**	n	–	–	+	–	–	+
***Candelariella aurella* (Hoffm.) Zahlbr.**	d	–	–	+	–	–	+
Candelariella xanthostigma (Pers.) Lettau		–	–	+	+	–	+
Chrysothrix chlorina (Ach.) J.R. Laundon		–	–	–	+	–	–
Cladonia coniocraea (Flörke) Spreng.	*a*	–	–	–	+	+	+
Cladonia fimbriata (L.) Fr.		–	–	–	+	+	+
***Diploschistes scruposus* (Schreb.) Norman**	dn	–	–	+	–	–	+
Hypocenomyce scalaris (Ach. ex Lilj.) Choisy	*a*	–	–	–	–	+	+
***Hypogymnia physodes* (L.) Nyl.**	*a*	–	–	+	–	–	+
***Hypogymnia tubulosa* (Schaer.) Hav.**	a	–	–	–	–	–	+
***Lecanora albellula* (Nyl.) Th. Fr.**		–	–	+	–	–	+
Lecanora albescens (Hoffm.) Flörke *f. lignicola*		–	–	–	–	+	–
Lecanora conizaeoides Nyl. in Cromb.	*a*	+	+	+	+	+	+
***Lecanora dispersa* (Pers.) Sommerf.**	dn	–	–	+	–	–	+
Lecanora expallens Ach.		–	–	–	+	+	–
Lecanora hagenii (Ach.) Ach.	*n*	–	+	+	+	+	+
***Lecanora muralis* Schreb.**	dn	–	–	+	–	–	–
Lecanora saligna (Schrad.) Zahlbr.[4]		–	+	+	+	+	+
Lecanora varia (Hoffm.) Ach.		+	–	–	+	–	–
***Lecidella elaeochroma* (Ach.) M. Choisy**		–	–	+	–	–	–
Lepraria incana (L.) Ach. s.l.	*a*	+	+	+	+	+	+
***Melanelixia fuliginosa* subsp. *fuliginosa* (Fr. ex Duby) O. Blanco**	a	–	–	–	–	–	+
***Melanohalea exasperatula* (Nyl.) O. Blanco**	n	–	–	–	–	–	+
***Micarea botryoides* (Nyl.) Coppins**		–	–	–	–	–	+

continued

***Micarea prasina* Fr.**		–	–	–	–	–	+
***Opegrapha varia* Pers.**		–	–	–	–	–	+
***Parmelia sulcata* Taylor**		–	–	–	–	–	+
Phaeophyscia nigricans (Flörke) Moberg	*dn*	–	–	+	–	+	+
Phaeophyscia orbicularis (Neck.) Moberg	*dn*	–	–	+	+	+	+
Physcia adscendens (Fr.) H. Olivier	*n*	–	–	+	+	+	+
Physcia caesia (Hoffm.) Fürnrohr	*dn*	–	–	+	+	–	+
Physcia dubia (Hoffm.) Lettau	*dn*	–	–	+	+	–	+
***Physcia stellaris* (L.) Nyl.**		–	–	+	–	–	+
Physcia tenella (Scop.) DC.	*n*	–	–	+	–	+	+
Physconia grisea (Lam.) Poelt	*dn*	–	–	+	+	+	+
Placynthiella uliginosa (Schrad.) Coppins & P. James		–	–	–	+	+	–
***Pseudosagedia aenea* (Wallr.) Hafellner & Kalb.**	n	–	–	–	–	–	+
***Pseudevernia furfuracea* (L.) Zopf**	a	–	–	+	–	–	+
Scoliciosporum chlorococcum (Graeve ex Stenh.) Vězda	*n*	+	+	+	+	+	+
***Strangospora pinicola* (A. Massal.) Körb.**		–	–	–	–	–	+
Trapeliopsis flexuosa (Fr.) Coppins & P. James	*a*	–	–	–	+	+	+
Xanthoria parietina **(L.) Th. Fr.**	n	–	–	+	–	–	+

[1, 2] Trees standing near the streets, in the Botanical Garden, in cemeteries, parks, gardens (Kiszka 1977, Kiszka and Kościelniak 1996).
[3] Trees in the Jordan Park, the Krakowski Park, the Bednarski Park, the Rakowicki Cemetery, the Botanical Garden and in the Wawel Hill near the Vistula River.
[4] *Lecanora saligna* counted together with the former *Lecanora sarcopis* (Wahlb.) Rohl

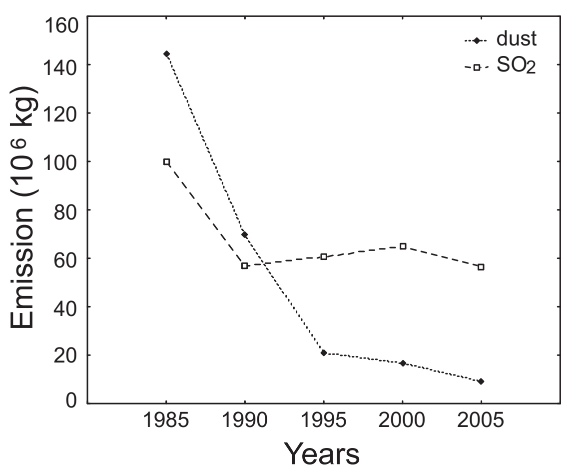

Fig. 3. Average annual emission of airborne particular matter PM_{10} and SO_2 in Małopolska Voivodship in the years 1985–2005 in particular years.

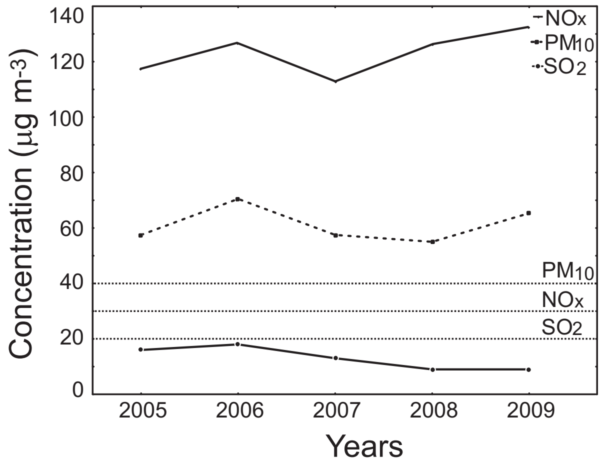

Fig. 4. Average annual concentration of dust (PM_{10}), SO_2 and NO_x in the atmosphere of Cracow in recent years (2005–2009). Standard levels (μg m^{-3}): PM_{10}-40; SO_2-20; NO_x -30.

these two main pollutants in Cracow do not, or slightly exceed standard levels but the high level of NO_x is still present (Fig. 4).

Air quality data have been provided for Cracow and Małopolska from the air monitoring network in the Małopolska region and reports by the Voivodship Inspectorate for Environmental Protection in Cracow.

2.3. Epiphytic lichen vegetation in the Cracow centre – state till 1990s

In the 1970s the Old Town area was a part of 'lichen desert', which spread throughout the city centre, except for parks and cemeteries (Kiszka 1977). In the Old Town and surrounding areas less than 1% out of more than 900 investigated tree trunks supported single, minute and damaged crustose lichen thalli. Lichens developed only in cracks of the trees bark. No major changes were observed twenty years later by Kiszka and Kościelniak (1996). Epiphytic lichens found in the city centre both in 1977 and in 1996, were only crustose species: *Amandinea punctata*, *Bacidina phacodes*, *Lecanora conizaeoides*, *Lepraria incana* s.l. and *Scoliciosporum chlorococcum* (Kiszka 1977, Kiszka and Kościelniak 1996) (Table 1). The most abundant species was *Lecanora conizaeoides*, however green alga *Pleurococcus viridis* dominated. Outside the city centre, mainly in parks, gardens and cemeteries, 20 epiphytic lichen species were found (Table 1) both in 1970s and in 1990s (Kiszka 1977, Kiszka and Kościelniak 1996).

Many individuals collected during the studies by Kiszka (1977), and Kiszka and Kościelniak (1996) were to some degree damaged or deformed. Thalli were undeveloped or unable to produce spores. Shrinking, necrotic fragments were observed not only on foliose thalli of the genus *Physcia*, but even on crustose thalli of *Lecanora conizaeoides*. However, in 1996 some occurrences of young, healthy specimens were noted, mainly in the outskirts of the city, but also in the Botanical Garden and the Rakowicki Cemetery (Kiszka and Kościelniak 1996). The richest biota was found on old willow trees, ash trees and poplars (Kiszka 1977).

3. MATERIAL AND METHODS

3.1. Field studies

Field studies were carried out in the years 2007–2009 in the centre of Cracow, in 7 localities: the Old Town, and six urban green areas. Within each locality deciduous trees (with only three exceptions) with the highest number of lichen species were chosen as study sites. Trees totally devoid of lichens were extremely rare in the study area and were not taken into account when performing analyses. A study site was defined as a single tree or rarely a group of two to three trees of the same species. Within the Old Town (the Market Square and the adjacent Planty Park) (Fig. 5), which was a part of a former 'lichen desert' (Fig. 1), 288 study sites were selected. The remaining 146 sites were located in the 6 localities around the Old Town: Jordan Park (28 sites), Krakowski Park (17 sites), Rakowicki Cemetery (23 sites), Botanical Garden (11 sites), Bednarski Park (57 sites) and the area near the Vistula River, located next to the Wawel Hill (10 sites) (Fig. 5). Although this last area belongs to the Old Town, it was treated separately because of the direct vicinity of the Vistula River and increased air humidity, which can strongly affect lichen growth.

Tree trunks were investigated from their bases to about 180 cm from the ground. Lichen species present and their cover (estimated as a percentage of the investigated surface) were recorded, together with general information about each site (localization, tree species, trunk girth). Samples for further taxonomic identification were collected when necessary. Additional information about any abnormalities of morphology of thalli (colour, shape; small but healthy thalli without soralia or apothecia were considered as young) was also gathered.

3.2. Analysis methods

The results were compared with corresponding data from the previous studies (Kiszka 1977, Kiszka and Kościelniak 1996). Significance of differences in species richness between localities were tested using one-way analysis of variance (ANOVA), which was also employed to test the effects of tree species diversity and tree diameter on species richness at a site. Analogical analyses in the case of cover rate were performed using the Kruskal-Wallis one-way analyses of variance. Two sample proportion Z test was employed to analyse the difference in numbers of acidophilic and nitrophilic species. The statistical analyses were performed using STATISTICA software (version 9.0) (StatSoft, Inc. 2009).

Discrimination between acidophilic and nitrophilic species followed Smith *et al.* (2009), also other publications (van Herk 1999, Seaward and Coppins 2004, Davies *et al.* 2007) were taken into account. Species tolerance to SO_2 was assessed using the eleven-grade (0–10) biological scale by Kiszka (1992) which is the modification of the Hawksworth and Rose's qualitative scale (1970) adopted to Polish lichen biota composition.

The nomenclature was given according to Fałtynowicz (2003) and updated according to the *Index Fungorum* (http://www.indexfungorum.org). Aggregate names have been applied for *Lepraria incana* and *Lecanora saligna*. The species names used in the studies by Kiszka (1977) and Kiszka and Kościelniak (1996) were updated according to the *Index Fungorum* (http://www.indexfungorum.org).

4. RESULTS

4.1. General characteristics of lichen biota in the Cracow centre

A total of 39 epiphytic species were recorded at 434 sites, with almost 70% of the biota (26 species) being noted in the Old Town (Table 1). Six species (*Diploschistes scruposus, Hypogymnia tubulosa, Lecanora albellula, Micarea botryoides, Opegrapha varia, Strangospora pinicola*) are new to Cracow, and two of them (*Diploschistes scruposus* and *Lecanora albellula*) were found not only in parks, but also in the Old Town (Table 1). Twenty species were recorded for the first time in the study area (Table 1). Six species (*Buellia griseovirens*, *Chrysothrix chlorina*, *Lecanora albescens* var. *lignicola*, *L. expallens*, *L. varia*, *Placynthiella uliginosa*) which had been recorded previously form the study area (Kiszka 1977, Kiszka and Kościelniak 1996), were not found during the present survey (Table 1).

Four species are legally protected in Poland (*Hypogymnia tubulosa*, *Melanelixia fuliginosa*, *Melanohalea exasperatula*, *Pseudevernia furfuracea*) (Regulation by Polish Minister of Environment 2004) and three (*Hypogymnia tubulosa*, *Opegrapha varia*, *Strangospora pinicola*) are rare and have been included in the Red List of Plants and Fungi in Poland (Cieśliński *et al*. 2006).

Five species (*Candelariella aurella*, *Diploschistes scruposus*, *Lecanora dispersa*, *L. muralis, Physcia caesia*) usually reported in Poland from rocks and concrete (Fałtynowicz 2003), were currently observed on tree trunks – *Candelariella aurella*, *Diploschistes scruposus, Lecanora dispersa* and *Physcia caesia* in the whole study area, while *Lecanora muralis* in the Old Town at a single site only. *Candelariella aurella*, *Diploschistes scruposus* and the

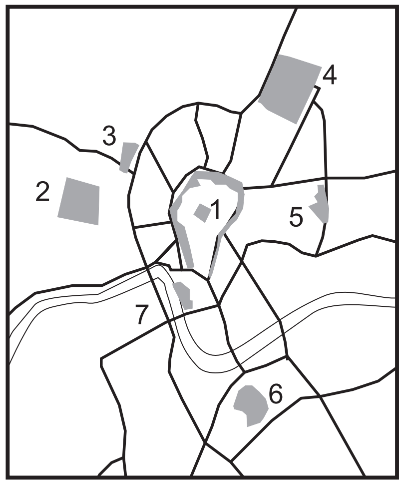

Fig. 5. The location of the study areas in city centre of Cracow (South Poland). 1 – Market Square with the Planty Park (the Old Town); 2 – the Jordan Park; 3 – the Krakowski Park; 4 – Rakowicki Cemetery; 5 – Botanical Garden; 6 – the Bednarski Park; 7 – the Wawel Hill

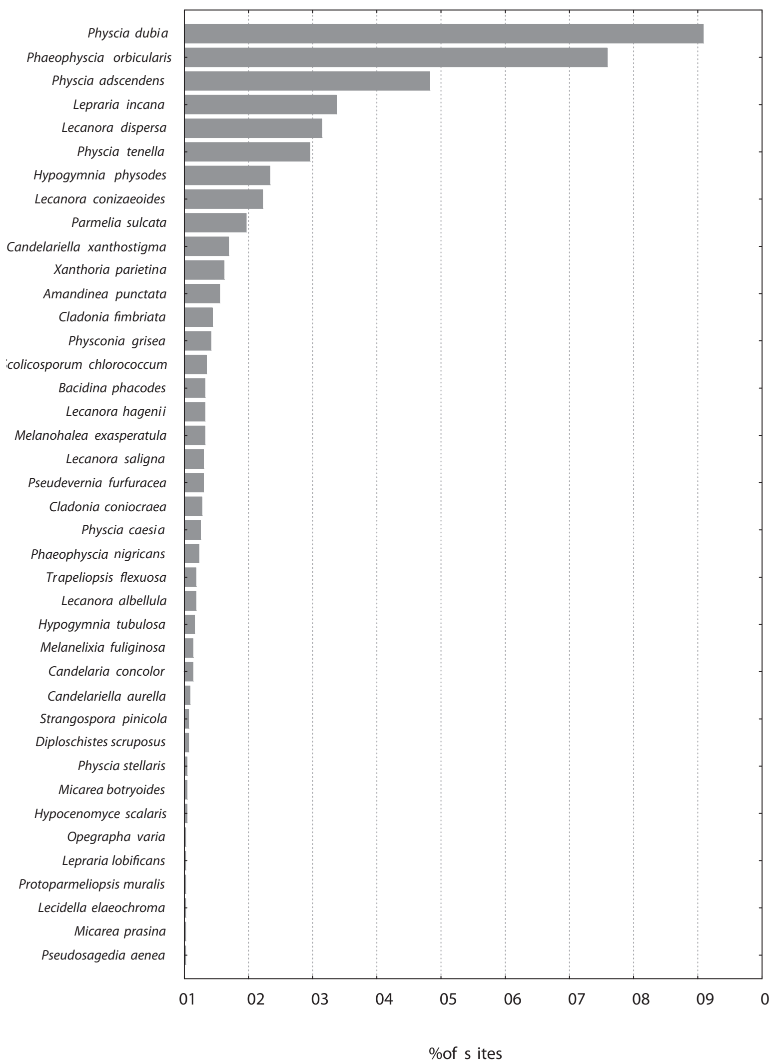

Fig. 6. Frequency (% of sites) of lichen species at all sites in the centre of Cracow (2009).

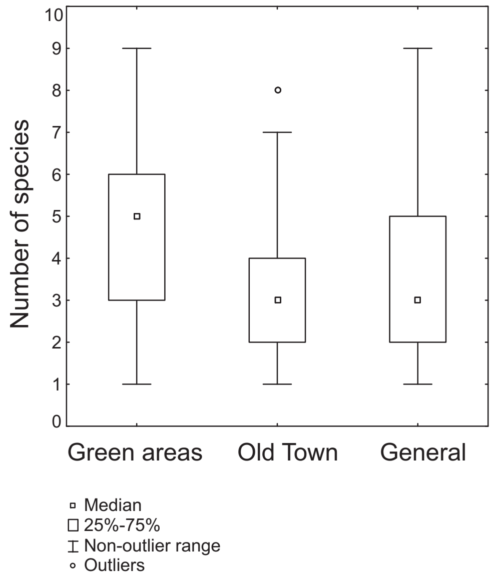

Fig. 7. The average number of lichen species at a site in all green areas together, in the Old Town and in the whole study area in general (2009).

two *Lecanora* species are new to the epiphytic lichen biota of the study area, while *Physcia caesia* was previously present on single trees close to the roads (Kiszka 1977) (Table 1).

The two commonest species in the investigated area were nitrophilic and dust tolerant *Physcia dubia* and *Phaeophyscia orbicularis* which occurred in more than 60% of all sites (Fig. 6). Two other nitrophytes, *Physcia adscendens* and *Lecanora dispersa*, together with acidophilic *Lepraria incana* s.l., were recorded in more than 20% of all sites. Nitrophilic *Physcia tenella* and acidophilic *Hypogymnia physodes* and *Lecanora conizaeoides* were recorded in more than 10% of all sites (Fig. 6).

As far as the tolerance to SO_2 is concerned, *Hypogymnia physodes, Phaeophyscia orbicularis* and *Physcia tenella* represent the 4th grade of Hawksworth and Rose's qualitative scale (Hawksworth and Rose 1970, Kiszka and Kościelniak 1996), *Physcia adscendens* belongs to the 3rd grade, while *Lepraria incana* s.l. and *Lecanora conizaeoides* belong to the 2nd grade. The most SO_2-sensitive lichens found during the present study – *Candelaria concolor* (1% of all sites), *Melanohalea exasperatula* (3%), *Opegrapha varia* and *Physcia stellaris* (both less than 1%) represent the 5th grade of Hawksworth and Rose's scale (Fig. 6).

The difference in numbers of acidophilic and nitrophilic species recorded in the whole study area is statistically significant (P <0.001).

Number of lichen species at a site spanned from 1 to 9. The majority of sites (25%) supported 3 different lichen species (Fig. 7). Sites with 4 or 5 species were also frequent, occupying 17 and 12%, respectively. It is a huge change in comparison with the former years when the majority of trees were devoid of lichens (Kiszka 1977, Kiszka and Kościelniak 1996). The locality with the highest average number of species at a site was the Jordan Park and with the lowest the Old Town (Figs. 7 and 8).

Coverage of most of the tree trunks was up to 10%, however in some cases the trunks were almost entirely (up to 90%) covered by lichens (Fig. 9). The locality with the highest average cover was Rakowicki Cemetery and with the lowest – the Wawel Hill (Fig. 10).

The most numerous trees in the study area were maples (*Acer* spp.), mainly *Acer pseudoplatanus,* representing more than one-third (overall 154) of all studied trees and dominating mostly in the Old Town. Maples supported the highest number of lichen species (overall 32 spp.). Other frequent tree species were: *Fraxinus excelsior* (overall 70), *Tilia cordata* (overall 34) and *Betula pendula* (overall 31). They also supported a high number of lichen species, overall 28 spp., 25 spp. and 25 spp., respectively. Analysis of variance showed that tree species and tree diameter diversity didn't contribute to the diversity of the number of species, as well as to the diversity of the cover rate.

The lichen thalli in the study area were generally healthy and well-developed. Many young individuals were also recorded. The most frequent damage observed on thalli were feeding traces of invertebrates. Thalli of *Lecanora conizaeoides* without apothecia were often recorded.

4.2. The Old Town

In the area of the Old Town a total of 26 epiphytic lichen species were recorded in 288 sites (Table 1), which is a huge change in comparison with the previous studies. Both of the most SO_2 sensitive lichens found during the present studies, *Candelaria concolor* and *Physcia stellaris*, were noted, at single sites, in this area.

The most abundant lichens were nitrogen- and dust-tolerant *Physcia dubia* and *Phaeophyscia orbicularis*, being noted at approximately three-quarters of all sites (83, and 76% of sites, respectively). Other frequent species, *Physcia adscendens*, *Lecanora dispersa* and *Physcia tenella*, also connected with nitrogen- and dust-enriched environment, were noted at 37, 24 and 22% of sites, respectively. Three most abundant acidophilic species, *Lepraria incana* s.l., was found at 10% of sites, and two other acidophytes, *Hypogymnia physodes* and *Lecanora conizaeoides*, at 7 and 6% of sites, respectively. Most of the study sites supported 3 lichen species (29%), however at two sites 8 species at a site were recorded (Fig. 7). Trees in the Old Town supported significantly less lichen species than those in other localities counted together (P <0.001) (Fig. 7). The biggest percentage of the sites (62%) had a cover rate up to 10%, and approximately one-quarter of sites (26%) was covered with lichens up to 20%. One site with a cover rate up to 80% was found (Fig. 9). Differences in coverage between the Old Town and other localities proved statistically significant (P <0.001). The Old Town, as well as the Wawel Hill (Fig. 10), are the two localities with the lowest average cover.

The lichen thalli were well-developed. Many young individuals were noted. Discoloured thalli, especially of *Xanthoria parietina*, were often recorded, mainly on the Market Square.

4.3. Green areas

In the six green urban areas a total of 37 epiphytic lichen species were recorded at 146 sites. The most abundant species was, as in the Old Town, nitrogen- and dust- tolerant *Physcia dubia*, being noted at almost 80% of all sites. Only in the Rakowicki Cemetery acidophilic *Lepraria incana* s.l. dominated (91% of 23 sites). The most SO_2 sensitive lichens found during the present studies, *Candelaria concolor, Physcia stellaris* and *Opegrapha varia,* were noted at single sites, only in the Bednarski Park. Most of the study sites (17%) supported 3 lichen species; sites with 4 and 5 different species were also frequent (15 and 16%, respectively) (Fig. 7). At six sites situated in the Jordan Park, 9 different species at a site were noted. The locality with the highest average number of lichen species at a site was the Jordan Park and with the lowest – the Bednarski Park (Fig. 8). The biggest percentage of the sites (46%) had a cover rate up to 10%, and more than one-fifth of sites (22%) was covered with lichens up to 20% (Fig. 9). Two sites, one in the Bednarski Park and second in the Rakowicki Cemetery, with a cover rate up to 90% were found. The locality with the highest average cover was the Rakowicki Cemetery and with the lowest - Wawel Hill (Fig. 10). The lichen thalli were mostly healthy, and often young.

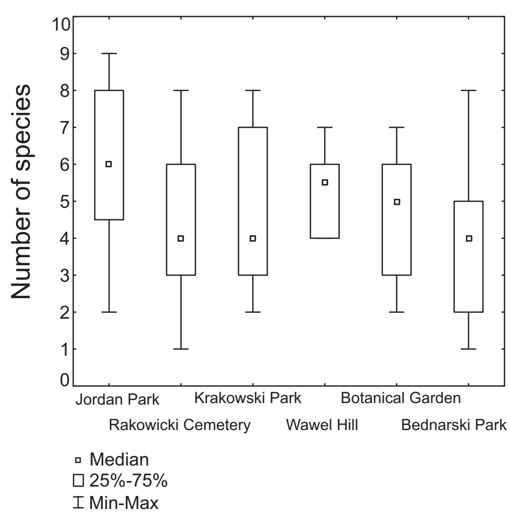

Fig. 8. The average number of lichen species at a site in each locality, included to green areas, separately (2009).

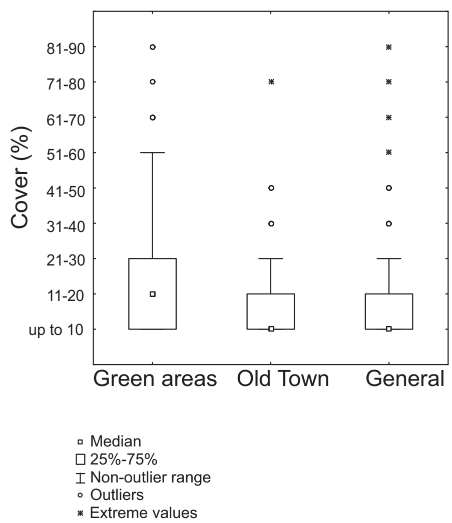

Fig. 9. The average lichen cover at a site in all green areas together, in the Old Town and in the whole study area in general (2009).

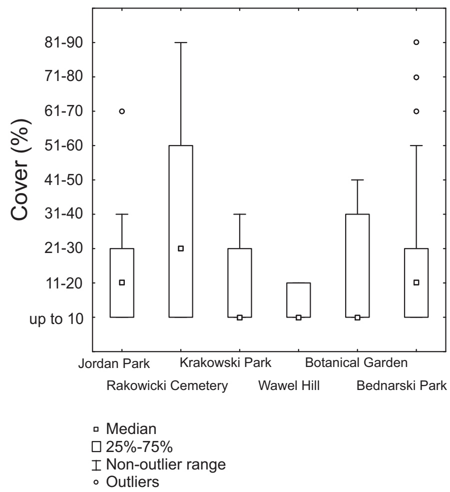

Fig. 10. The average lichen cover at a site in each locality, included to green areas, separately (2007).

5. DISCUSSION

During the last 10 years major changes in epiphytic lichen vegetation have taken place in the centre of Cracow, following the air quality improvement. As predicted, huge improvement in lichen vegetation is clearly seen. The 'lichen desert' is no longer present as a compact area, as it was in the 1990s (Fig. 1), and only single trees devoid of lichens are found. Places where formerly only extremely pollution tolerant lichens had been recorded, have now been colonized by more sensitive macrolichen species. Macrolichens were also recorded in the area of the former 'lichen desert'. In other cities where comparison with historical data was possible, the reduction of the 'lichen desert' was observed as well, *e.g.* in London (Rose and Hawksworth 1981), Rome (Munzi *et al.* 2007) and Torino (Isocrono *et al.* 2007). The authors agree that declining SO_2 concentration is the main factor responsible for this trend. The general improvement of lichen vegetation in the study area is in line with the results from both urban (*e.g.* Loppi *et al.* 2003, Hultengren *et al.* 2004, Isocrono *et al.* 2007) and industrial areas (*e.g.* Showman 1997, Ranta 2001, Bačkor *et al.* 2003) across Europe and North America. Similar results were also obtained in Skawina, Poland (Lisowska 2011). However, the general improvement of lichen vegetation is not always associated with the complete disappearance of 'lichen desert', as was the case *e.g.* in Pistoia, Central Italy. The presence of the 'lichen desert' in this town was explained by the constantly high levels of NO_x (Loppi and Corsini 2003).

More than a half of all taxa identified (20 species) are new to the study area. They are mostly nitrophilic and associated with dust contaminated substrata (Table1). Several of these species, *Candelariella aurella*, *Diploschistes scruposus*, *Lecanora dispersa* and *L. muralis*, rarely grow on trees in Poland, occupying mostly calcareous rocks and man-made substrata. Three of them (*Candelariella aurella*, *Lecanora dispersa, L. muralis*) had been present within the study area in the past, but limited only to rocks and concrete (Kiszka 1977, Kiszka and Kościelniak 1996). The appearance of epilithic lichens on trees in urban areas has been also observed elsewhere in Europe, *e.g.* in London (Davies *et al.* 2007, Larsen *et al.* 2007), as well as in Poland (Lisowska 2011). In the Netherlands appearance of epilithic species on trees was associated with increase in bark pH, which had been noted in this area (van Herk 2002, Wolseley *et al.* 2006). *Lecanora hagenii*, noted during present research on tree trunks, was previously recorded by Kiszka (1977) on decaying wood.

Several species currently present in the centre of Cracow, *e.g.* *Candelaria concolor,* *Hypogymnia physodes, Melanohalea exasperatula*, and *Pseudevernia furfuracea,* had been observed previously within the city boundaries, but mainly in the western part, only on the outskirts of the city. *Pseudevernia furfuracea* up till now has been recorded in three sites (Kiszka 1977) and later in one site only (Kiszka and Kościelniak 1996).

Some species recorded previously in a very few sites, were not found again in the present survey. It can be explained by their phorophytes being cut down or by differences in sampling sites. They may have also been overlooked during the field studies or did not manage to survive.

The commonest lichens in the study area were foliose species of medium tolerance to SO_2 (Hawksworth and Rose 1970). One fruticose macrolichen, *Pseudevernia furfuracea*, was also found. The most SO_2 sensitive lichens recorded (*Candelaria concolor*, *Melanohalea exasperatula* and *Physcia stellaris*) are classified to the 5th grade of Hawksworth and Rose's (1970) scale. This suggests that SO_2 level is no longer a limiting factor for epiphytic lichens in the centre of Cracow, that corresponds with other studies (*e.g.* Purvis *et al.* 2003).

The majority of the species in the study area, including the most frequent ones, are nitrophilic (Table 1), which is in agreement with numerous studies (*e.g.* van Herk 1999, Seaward and Coppins 2004, Wolseley *et al.* 2006, Davies *et al.* 2007). The dominance of nitrophilic species is also reported from other European cities and towns. For example, in London the most common species are *Physcia adscendens* (Purvis *et al.* 2003), presented on 70% of the examined trees, together with *Xanthoria parietina* and *Phaeophyscia orbicularis* (Davies *et al.* 2007). Similarly, in Torino *P. orbicularis* and *P. adscendens*, present in over 80% of the sampling stations, are the most common species (Isocrono *et al.* 2007). However, in Rome (Munzi *et al.* 2007) epiphytic lichens recorded are known to prefer acid and subacid bark, what can be associated with the proximity of the sea, as is the case in Portugal (Pinho *et al.* 2008).

On the other hand, two species considered as acidophytes (van Herk 2002), *Lepraria incana* s.l. and *Hypogymnia physodes*, were frequently observed in the study area, as was the case *e.g.* in Torino, Italy (Isocrono *et al.* 2007). Although *Lepraria incana* s.l. prefers lower substratum pH, it seems to be tolerant to NO_x (Davies *et al.* 2007), which might explain its high frequency in the study area. Conversely, *Hypogymnia physodes* seems to be very sensitive to NO_x (Bates *et al.* 2001). Several authors (*e.g.* van Herk 2001; Hultengren *et al.* 2004, Sparrius 2007) have shown a significant decline of *H. physodes* in several European countries. In SE England, for example, despite it was by far the most common macrolichen recorded on oak trees, it had shown a spectacular decrease with falling SO_2 (Bates *et al.* 2001). The continuing decline of this species was also confirmed by Purvis *et al.* (2003) and Davies *et al.* (2007) in London. According to Purvis *et al.* (2003) NO_x coupled with particles, and not falling SO_2 level, were the major factors responsible for damaging *Hypogymnia physodes* near London.

Strongly acidophilic *Lecanora conizaeoides* was not a very frequent species in the study area, being noted in less than 15% of sites, which corresponds with the considerably low SO_2 level (Fig. 3). This lichen often grows in SO_2- polluted areas where more sensitive species are not able to exist, and it used to dominate in urban and industrial areas for a long time, as long as the SO_2 level in the atmosphere remained high (Bates *et al.* 2001, Larsen *et al.* 2007, Davies *et al.* 2007). The decline of SO_2 concentrations in recent years has caused loss of *L. conizaeoides*, *e.g.* in Skawina, Poland (Lisowska 2011), and also in SE England (Bates *et al.* 2001), where it was explained by the fact that this species require elevated SO_2 inputs (or some closely related chemical factor) for healthy growth. There may be also other explanations for this. According to recent investigations (Hauck *et al.* 2008) the extremely high SO_2 tolerance in lichens is strongly correlated with hydrophobicity of the thallus surface. Thus the success of *L. conizaeoides* in SO_2 polluted areas can be attributed to the superhydrophobicity of its surface and also to its high dispersal ability (Hauck *et al.* 2008). Other factors *e.g.* competitive interactions with other epiphytes and attacks by the parasitic fungus *Athelia arachnoidea* were also taken into consideration (Bates *et al.* 2001, Hultengren *et al.* 2004). This might be the case in Cracow, since many fungus-infected specimens were observed during the present study. The competition with dust and nitrogen tolerant *Lecanora dispersa* and other ecologically similar species might be also a limiting factor. Most likely *Lecanora conizaeoides* will not increase significantly in the coming years.

Many grayish specimens of normally yellow nitrophilic *Xanthoria parietina* were found during the current studies, mainly in the Market Square. The same tendency was observed in London by Davies *et al.* (2007) and explained by the fact that orange colour of the thallus is inversely related to NO_x. This suggests the considerably high level of NO_x in the Cracow centre.

Currently, the main source of atmospheric NO_x pollution in Cracow is most likely vehicular traffic. In the whole Małopolska Voivodship the number of road vehicles is steadily increasing. In the years 2000–2009 the number of registered passenger vehicles increased by almost 66%, from *ca* 829 000 to *ca* 1 375 000 (Statistical Office in Cracow 2010), and further increase is very probable. Since the level of SO_2 is relatively low, transport-related NO_x is considered to have a major impact on lichen distribution and diversity in the study area. Numerous studies support this scenario. In Montecatini Terme, Central Italy (Loppi *et al.* 2004), as well as in Genova province, NW Italy (Giordani 2007), despite the general improvement of lichen vegetation, lichen presence is negatively affected by NO_x derived from vehicular traffic. In the case of Seville, Spain (Fuentes and Rowe 1998) 'lichen desert' still exist due to high traffic vehicles emissions. In Pistoia, Central Italy (Loppi and Corsini 2003), lichen recolonization is determined by declining SO_2 concentrations, while major injuries to lichen communities are caused by the constantly high levels of NO_x. The combination of suspended particles and nitrogen from traffic emissions also seems to influence lichen growth (Purvis *et al.* 2003, Isocrono *et al.* 2007). However, whereas SO_2 is highly toxic, nitrogen is a nutrient and only becomes toxic in excess to those species that are sensitive (Wolseley *et al.* 2006). Positive correlation between nitrophytes and road proximity was established *e.g.* in Grenoble, France (Gombert *et al.* 2003, Gombert *et al.* 2004). On the other hand, no associations between NO_2 concentrations and the diversity of epiphytic lichens in the proximity of a rural highway in Central Italy was found, probably because of low NO_2 values measured (Frati *et al.* 2006). This suggests that in the coming years the kind of the effect of NO_x on lichens in Cracow will strongly depend on its level in the air. Synergistic effects of SO_2 and NO_x, which are observed when concentrations are below, or at the threshold for, individual injury response (Balaguer *et al.* 1997), also cannot be neglected. It is often very difficult to separate the effects of different pollutants (Loppi *et al.* 2002), especially when their levels are low.

Nitrophilic lichens, such as *Phaeophyscia orbicularis*, *Physcia* spp. and *Xanthoria parietina* were found most often in the study area on poplars (*Populus* spp.), while acidophilic *Hypogymnia physodes*, *Lecanora conizaeoides* and *Lepraria incana* s.l. preferred *Quercus robur* and *Betula pendula*, which have acid barks. Many authors agree that bark pH, increasing in response to declining SO_2 levels, had caused shifts in the epiphytic lichen biota observed in polluted areas (van Dobben and Ter Braak 1999, van Herk 2001, Marmor and Randlane 2007, Sparrius 2007). Davies *et al.* (2007) suggested that generally while nitrophytes are connected with transport-related pollutants, acidophytes are associated with bark pH. In the centre of Cracow, while generally bark pH must have increased in response to the falling SO_2, no substrate over-eutrophication is visible, since the ecological preferences of lichen species and bark pH of the phorophytes seem to be well linked. On the other hand, according to the most recent research (Spier *et al.* 2010) the more important factor influencing lichen vegetation may be the tree species, while bark pH alone is of less importance. Also other factors *e.g.* tree age, roughness, water holding, capacity, other bark chemical properties besides pH etc. may play a role (Spier *et al.* 2010). However, during the current studies neither tree species, nor trunk diameter had a statistically significant effect on the lichen species richness.

Both species richness and cover differ significantly between localities, the lowest values being recorded in the Old Town and the Wawel Hill. This corresponds with the extent of the former 'lichen desert'. However, within the former 'lichen desert' some of the most SO_2 sensitive and rare macrolichens were recorded. This indicates high speed and intensity of the colonization process, which led to such vast changes in less than fifteen years. Further improvement is expected, as many young individuals were recorded. Long-term research, including the whole area of Cracow, would be of great importance in monitoring future changes in lichen vegetation and assessing the air quality in the city.

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